

Inhibition of Premixed Methane-Air Flames by Water Mist



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Introduction



- Halon 1301 (CF_3Br) was widely used agent in total flooding fire suppression systems
- Production ban in 1994 created need for replacement agents
- Water is a promising alternative to halon for many applications; favorable properties include:
 - zero ozone depletion
 - zero global warming potential
 - non-toxic
 - inexpensive agent
 - effective at fire suppression



Practical Considerations



- Liquid at room temp; must work with drops
 - Drop generation; suitable quantities at optimum size
 - Drop quantification and monitoring
 - Physics of multi-phase flow; engineering issues
 - Flow dynamics: need to get water to fire
- Drop size matters
 - Small drops ($d < 100 \mu\text{m}$) most effective
- How effective can water be under ideal laboratory conditions?

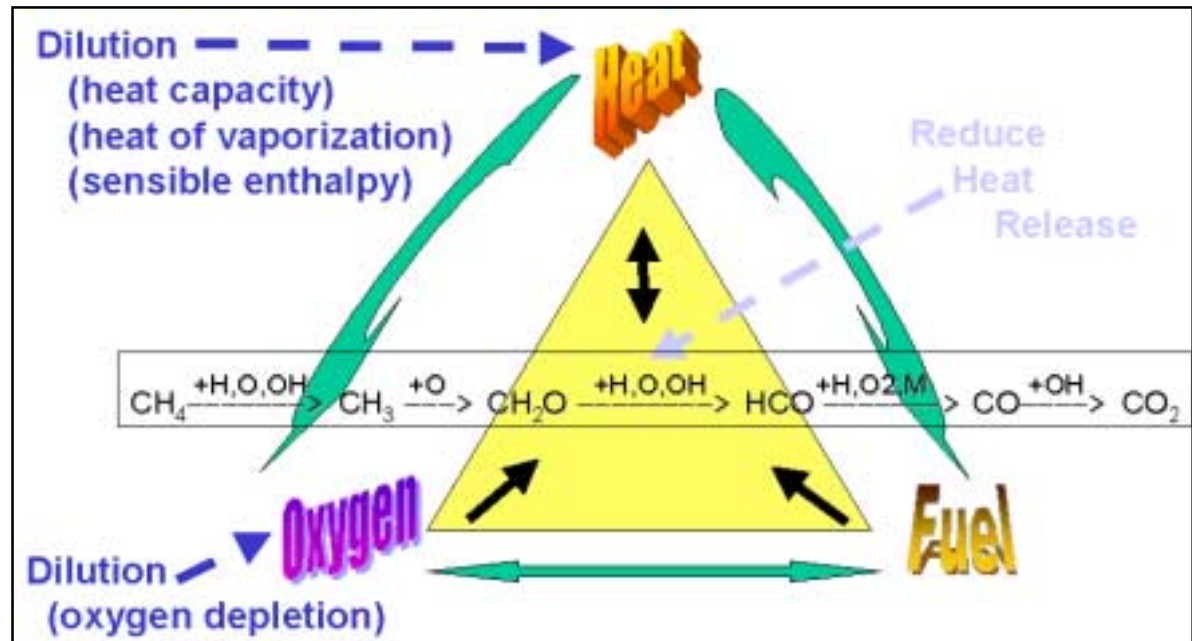


Water is a Thermal Agent



Inert thermal agents:

Increase heat capacity
Lower flame temperature
Reduce progress of flame
Dilute oxygen



=>Results in reduced burning velocity of premixed flames

Water is a good thermal agent

- Large latent heat of vaporization of **liquid water** provides significant contribution to suppression effectiveness

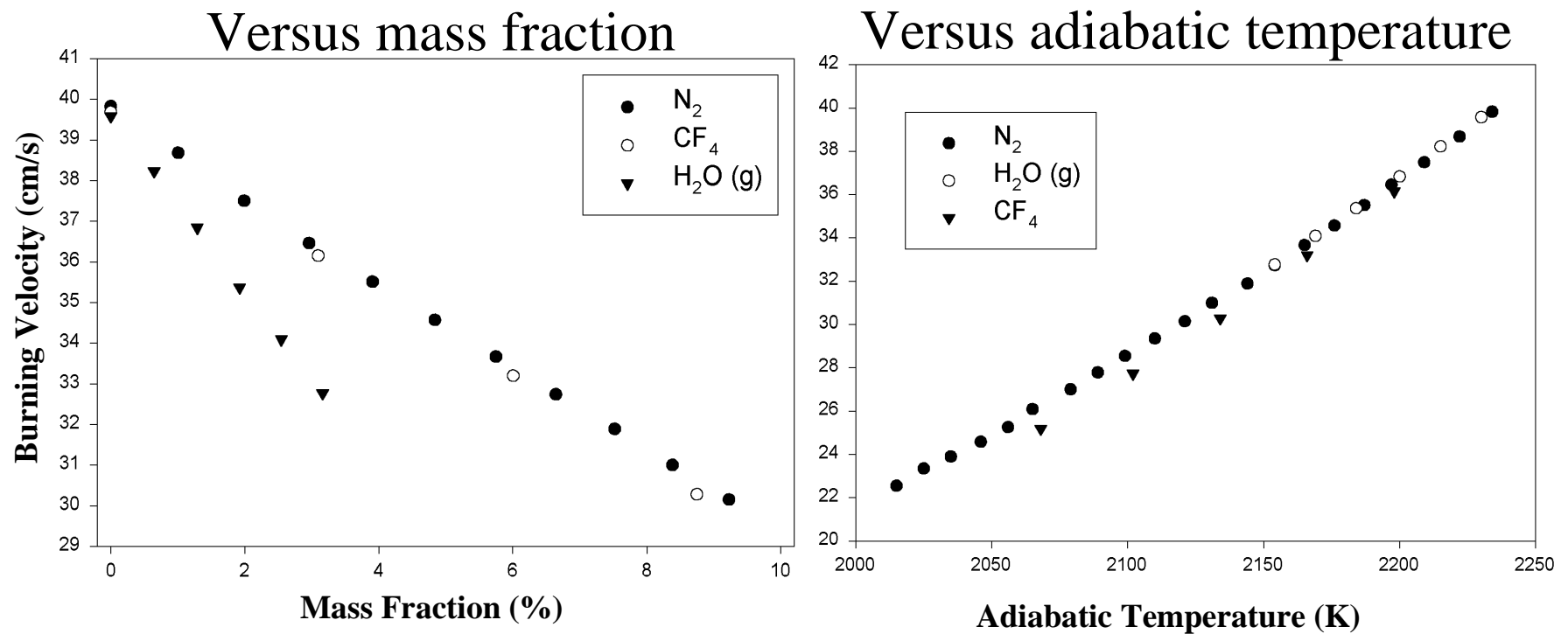


Thermal Agent Effect on Burning Velocity



Both modeling and experimental studies show that there is a linear reduction in burning velocity with addition of gaseous thermal agents

PREMIX calculations of flame speed -
Comparison of N_2 , CF_4 , and water vapor





Thermodynamic Properties



Agent	$H_f^{2200} - H_f^{298}$	
	$\frac{\text{kJ}}{\text{g}}$	$\frac{\text{kJ}}{\text{mol}}$
N ₂	2.3	63
CF ₄	2.1	184
H ₂ O (vapor)	4.6	83
H ₂ O (liquid)	7.1	127
CF ₃ Br	1.3	189

Reduction in flame temperature
determined by sensible enthalpy:

$$H_f(\text{Flame T}) - H_f(\text{Room T})$$

- On mass basis N₂ and CF₄ have similar heat capacities
- Liquid water has three times the sensible enthalpy per unit mass as N₂ or CF₄
- 1/3 of sensible enthalpy of liquid water comes from vaporization



Burning Velocity of Premixed Flames



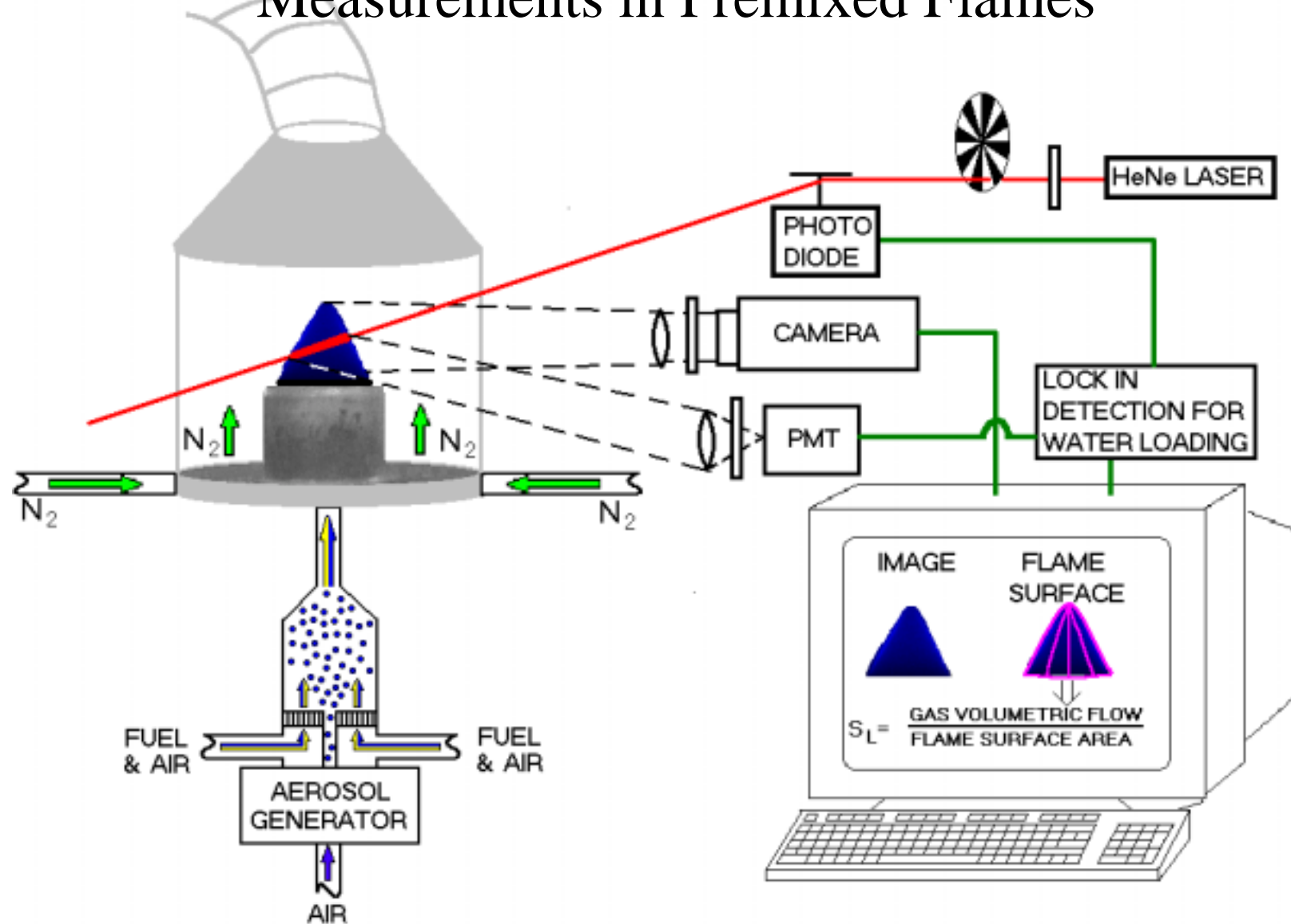
- **Reduction of burning velocity** is the best measure of inhibition in a premixed flame
- Burning velocity is determined by total area method using flame surface area:

$$\text{Burning Velocity} = \frac{(\text{Mean bulk velocity})(\text{burner diameter})}{\text{flame surface area}}$$

- **Flame surface area** can be derived from schlieren, shadow image, or **luminous flame image**
- Luminous flame image used in study
- Burning velocities are normalized to that of the uninhibited flame removing uncertainties associated with absolute velocity determination



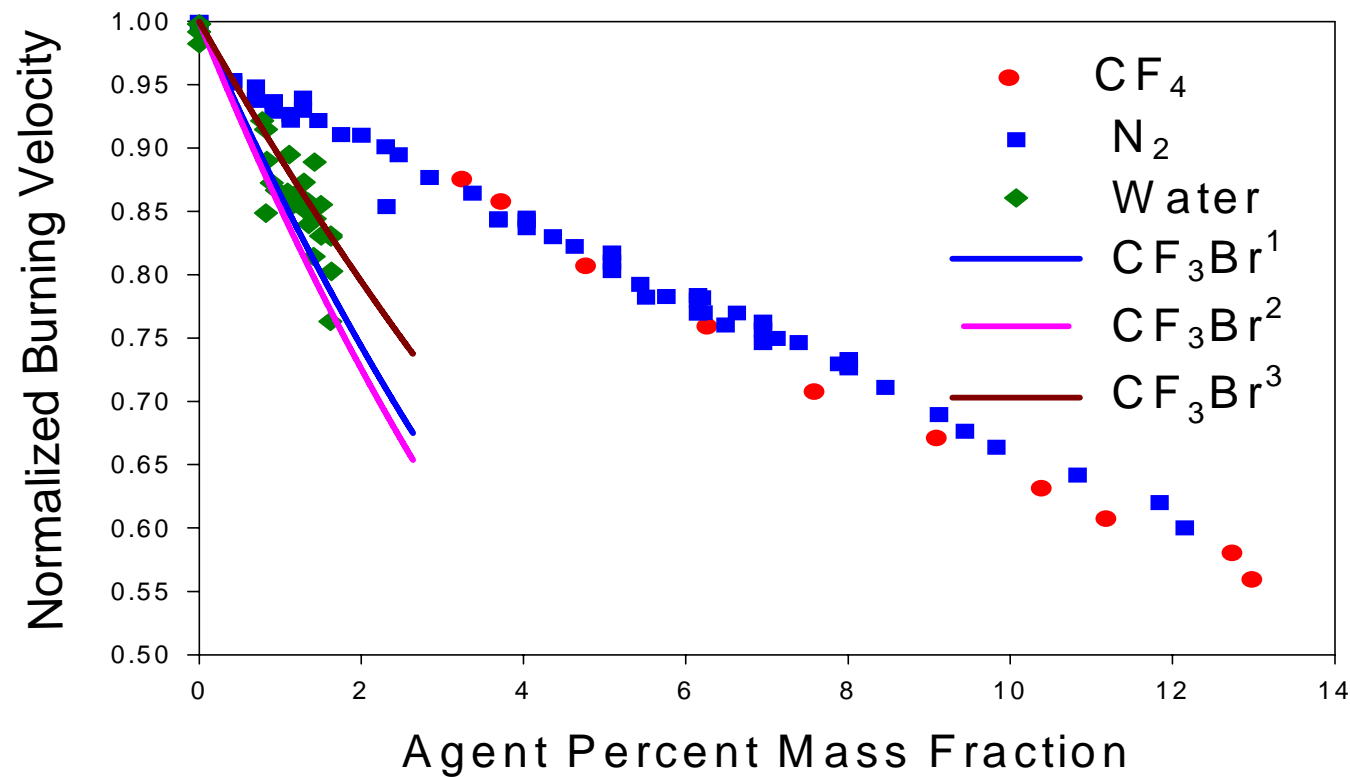
Water Mist-Inhibited Burning Velocity Measurements in Premixed Flames





Submicron Water Mist Reduction of Premixed Methane-Air Flame Burning Velocity

As effective as CF_3Br , Halon 1301



¹Sanogo, 1993, Ph.D. Dissertation, Universite d'Orleans, France.

²Parks et al., 1979, *Fire Safety J.*, **2**: 237-247.

³Noto et al., 1998, *Comb. Flame*, **112**: 147-160.



Methane-Air Flame Burning Velocity Reduction by Selected Agents



Agent	$H_f^{1600} - H_f^{300}$		Percent Mass Fraction (20% Reduction)	Percent Mole Fraction (20% Reduction)	$(H_f^{1600} - H_f^{298}) * (X_{\text{agent}}/X_{\text{O}_2})$ (kJ/mol)
	$\frac{\text{kJ}}{\text{g}}$	$\frac{\text{kJ}}{\text{mol}}$			
N ₂	1.5	42	6.3 ± 0.1	6.2 ± 0.1	14.6 ± 0.3
CF ₄	1.4	122	5.5 ± 0.1	1.9 ± 0.1	12.1 ± 0.7
H ₂ O (mist)	5.2	93	1.8 ± 0.2	2.7 ± 0.2	13.5 ± 1.0
CF ₃ Br ¹	0.8	1.9	1.9	0.4	2.5

¹ Noto *et al.*, 1998, *Comb. Flame*, **112**: 147-160.



Comparison of Water and Halon 1301



- Chemical suppression effects dominate in CF_3Br
 CF_3Br more efficient than N_2 or CF_4 and comparable to water mist even though CF_3Br has a lower sensible enthalpy per unit mass
- Effectiveness of water requires total vaporization



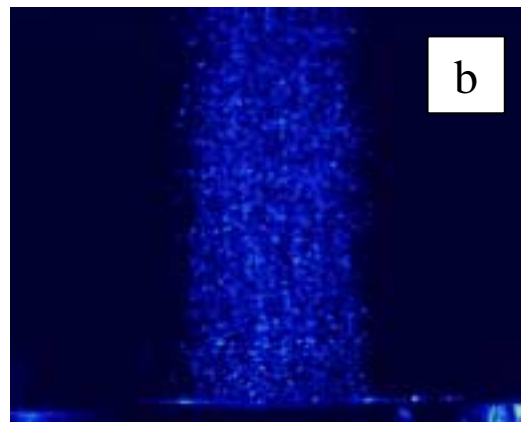
Maximum Effectiveness Achieved Because of Complete Evaporation



Sub-micrometer diameter drops completely evaporate before leaving flame



Flame only



Laser sheet
illumination of
drops, no flame

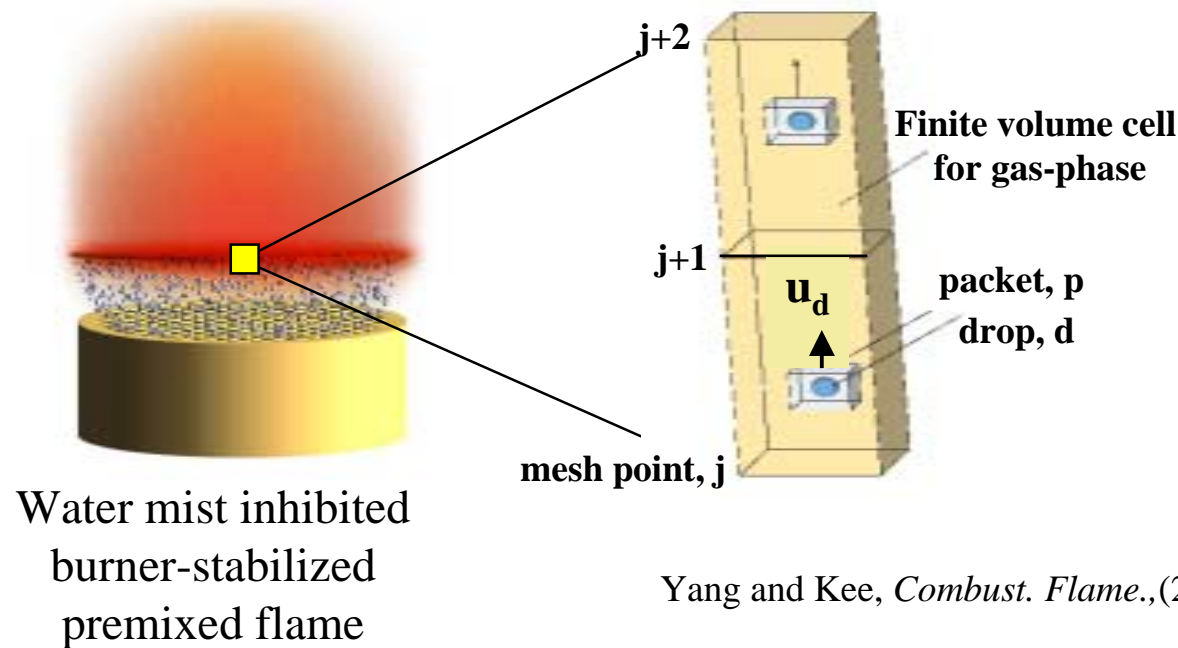


Flame and laser sheet
illumination of drops



Two-Phase Modeling Approach

- Eulerian formulation of gas-phase flame coupled with Lagrangian formulation of the drops
- Extension of PREMIX - addition of drop evaporation related source terms
- Boundary-value problem solving governing equations for gas phase
 - Chemical reaction mechanism, thermodynamic and transport properties from GRI-Mech 3.0 (nitrogen chemistry removed)
- Burner-stabilized flame with options for finding flame speed



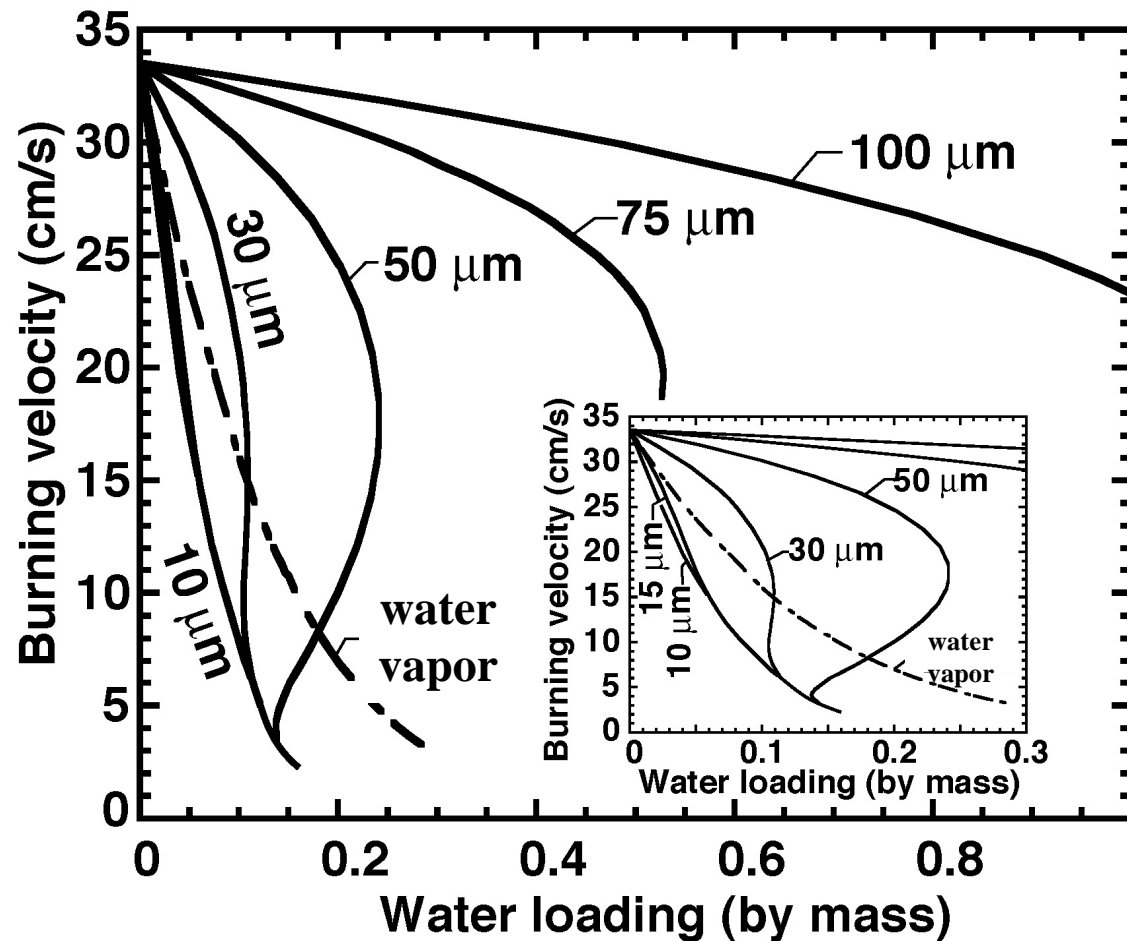
Yang and Kee, *Combust. Flame.*, (2002) accepted.



Predicted Water Mist Effect on Premixed Burning Velocity

Effectiveness plateau below $\sim 10 \mu\text{m}$

Non monotonic suppression behavior with loading for large drops

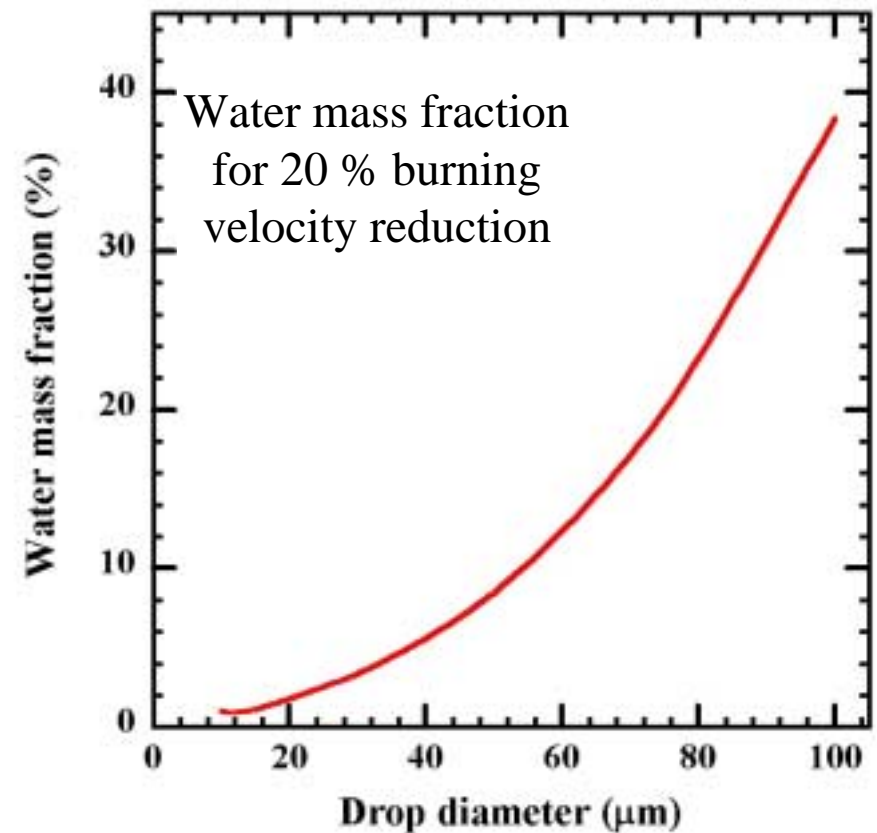
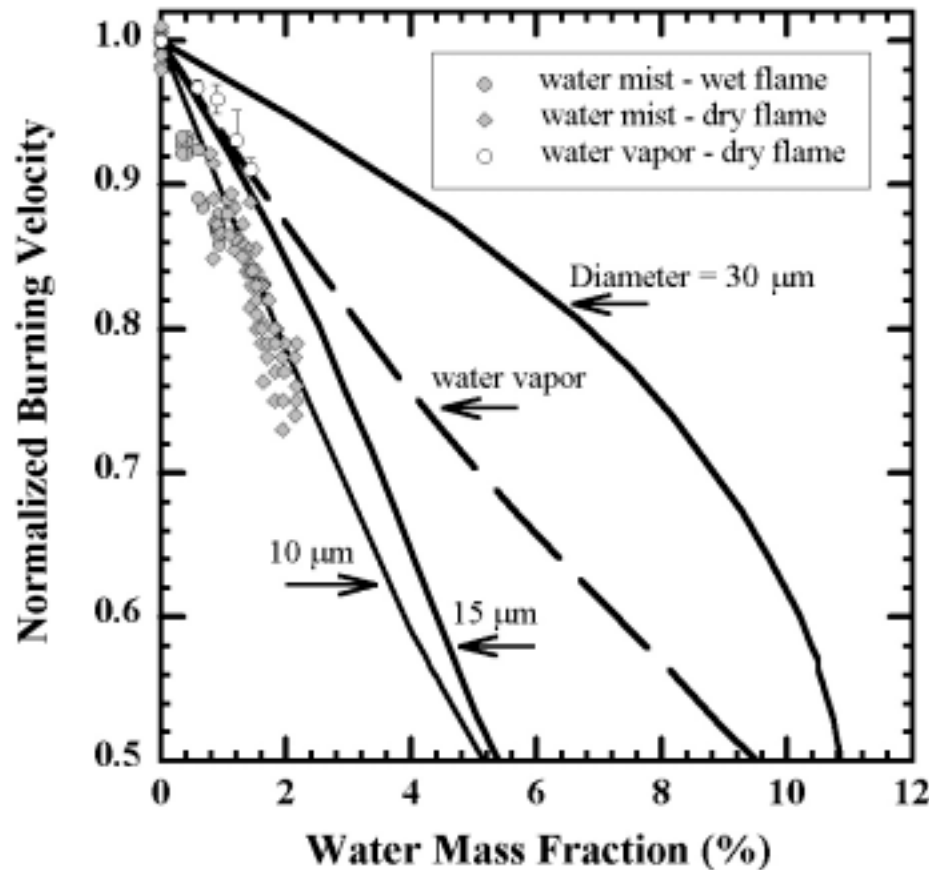


Yang and Kee
Combust. Flame
(2002) accepted.



Water Aerosol Inhibition of Premixed Methane/Air Flames

Experimental results (symbols) in excellent **agreement** with modeling predictions for sub-micron **water drops** and **water vapor**



~2%



Conclusions



- **Water mist** is as **effective** as **Halon 1301** (CF_3Br) on mass basis in inhibiting premixed methane-air flames for small drops: maximum suppression achieved
- Suppression effectiveness consistent with thermodynamic analysis based on **complete evaporation** of the small water drops ($\sim 0.35 \mu\text{m}$ diameter)
- **Measured** suppression effectiveness of small drops and water vapor in **excellent agreement** with multi-phase **model**, requiring no adjustable parameters
- Model predicts a plateau in suppression effectiveness at small drop size and a non-monotonic suppression effectiveness with increased loading for larger drops



Acknowledgements



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- Mr. Derek Dye, U Maryland - Baltimore County, Computer Science (NRL Student Intern May 1997-May 2000)



How good should water be?



To a good approximation, inert agents cause equal reductions in burning velocity for equal reductions in adiabatic flame temperature.

But, the mass of agent required varies:

Water vapor twice as effective as nitrogen or CF_4

Liquid water: enthalpy of vaporization 50% as large as enthalpy of heating to 2200K.

So liquid water should be **3 times better** than nitrogen.